

# $B_s \rightarrow \mu\tau$ and $h \rightarrow \mu\tau$ decays in the general two Higgs doublet model

Jong-Phil Lee

*Sang-Huh College, Konkuk University, Seoul 05029, Korea*

Kang Young Lee\*

*Department of Physics Education & Research Institute of Natural Science,  
Gyeongsang National University, Jinju 52828, Korea*

(Dated: December 14, 2016)

Inspired by the recent measurement of the  $h \rightarrow \mu\tau$  decays by the CMS collaboration at the LHC, we study the lepton flavour-violating (LFV)  $B_s \rightarrow \mu\tau$  decays in the general two Higgs doublet model. Those LFV interactions could accommodate the present deviation of the muon anomalous magnetic moment and also predict the LFV  $\tau$  decay processes such as  $\tau \rightarrow \mu\mu\mu$  and  $\tau \rightarrow \mu\gamma$ . We find that the  $B_s \rightarrow \mu\tau$  decay rates can be large with above experimental conditions in the framework of our model. These processes are expected to be observed at the colliders such as LHCb and Belle-II in the future.

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\* kylee.phys@gnu.ac.kr

## I. INTRODUCTION

The discovery of a Higgs boson [1, 2] has opened a new era of particle physics. Henceforth we have to explore the properties of this new boson in detail and try to understand the whole structure of the Higgs sector. Recently the CMS collaboration has reported a slight excess of an exotic decay mode of the Higgs boson into the  $\mu\tau$  final states [3]. The best fit value of the branching ratio is  $\text{Br}(h \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$  which shows a  $2.4\text{-}\sigma$  deviation from the null result predicted in the standard model (SM). The measurement of the ATLAS collaboration also shows a deviation but still less significance than the CMS result,  $\text{Br}(h \rightarrow \mu\tau) = (0.77 \pm 0.62)\%$  [4]. The combined result is given by

$$\text{Br}(h \rightarrow \mu\tau) = (0.82^{+0.33}_{-0.33})\% \quad (1)$$

and presents a upper limit to be  $1.39\%$  at  $95\%$  C.L..

Since  $h \rightarrow \mu\tau$  decays are the lepton flavour-violating (LFV) processes and forbidden in the SM, the excess could be a direct evidence of the new physics (NP) beyond the SM if it will be confirmed with more data in the future. Lots of studies of the new physics explanation on the excess of  $\text{Br}(h \rightarrow \mu\tau)$  has been provided in many literatures [5]. In this letter we consider the general extension of the SM with 2 Higgs doublets. The flavour-changing neutral current (FCNC) interactions with scalars are generated at tree level if the additional Higgs doublets exist without some flavour conserving mechanism. Thus the  $h \rightarrow \mu\tau$  decays arise in the general multi-Higgs doublets models.

The new scalar- $\mu$ - $\tau$  interactions provide various phenomenological implications. First they generically contribute to the muon anomalous magnetic moment,  $(g-2)_\mu$ . The precise measurement of  $(g-2)_\mu$  has been one of the most sensitive probe of the NP and still shows unexplained deviation from the SM prediction more than  $3\text{-}\sigma$  at present [6]. The scalar LFV interactions are helpful to accommodate the deviation [7, 8]. On the other hand, the LFV  $\tau$  decays are also predicted with the scalar FCNC, while they are absent in the SM. Thus the present experimental limits of  $(g-2)_\mu$  and the LFV  $\tau$  decays provide stringent constraints on the model.

Here we consider the LFV  $B_s \rightarrow \mu\tau$  decays in the general two Higgs doublet model (2HDM). The rare  $B$  decay modes involving the FCNC are very good testing ground to find hints for NP and have been studied in various channels. For instance, the  $B_s \rightarrow \mu^-\mu^+$  decays have been in the spotlight to explore the large supersymmetry contribution with scalar exchanges. Recently the branching ratio of  $B_s \rightarrow \mu^-\mu^+$  mode is measured by the LHCb and the CMS to be  $\text{Br}(B_s \rightarrow \mu^-\mu^+) = (3.1 \pm 0.7) \times 10^{-9}$  [9, 10] which agrees with the SM prediction. We note that  $\text{Br}(h \rightarrow \mu^-\mu^+)$  is of order  $10\%$ , two order higher than the best fit value of  $\text{Br}(h \rightarrow \mu\tau)$ . Assuming the SM Higgs mediated process is dominated in  $B_s \rightarrow \mu\tau$  decays, the ratios of  $B_s \rightarrow \mu\tau$  to  $B_s \rightarrow \mu\mu$  decays are comparable with those of  $\text{Br}(h \rightarrow \mu\tau)$  to  $\text{Br}(h \rightarrow \mu\mu)$ . Then we estimate the branching ratio of  $B_s \rightarrow \mu\tau$  to be of order  $10^{-11}$  and it is hard to be measured in the near future. If there are additional contributions to  $B_s \rightarrow \mu\tau$  decays, however, its branching ratio might be large enough to be observed while  $\text{Br}(B_s \rightarrow \mu\mu)$  being kept to be within the present measurement [14]. We explore the possibility of such enhancement including the other scalar contributions in the general 2HDM framework.

The paper is organized as follows. We briefly describe the lepton flavour-violation in the general two Higgs doublet model and obtain the scalar- $\mu$ - $\tau$  couplings from the experiments including the  $h \rightarrow \mu\tau$  decays measured at the LHC and  $(g-2)_\mu$  in Sec. II. In Sec. III, we consider the LFV  $\tau$  decay processes in this model. In Sec. IV, the  $B_s \rightarrow \mu\tau$  decays are studied under the experimental constraints discussed in the previous sections. Section V is devoted to conclusions.

## II. LEPTON FLAVOUR-VIOLATION IN THE GENERAL 2HDM

We can choose a basis for the two Higgs doublets  $\hat{H}$  and  $\hat{\Phi}$  where only one Higgs doublet  $\hat{H}$  gets a vacuum expectation value (VEV) and is responsible for the electroweak symmetry breaking [7, 11]. After an appropriate rotation of leptons such that the neutral components of  $\hat{\Phi}$  has flavour-diagonal couplings, the relevant Lagrangian for Yukawa interactions of leptons and d-type quarks reads

$$\begin{aligned} \mathcal{L} = & \frac{\sqrt{2}}{v} (m_e \bar{e}_L e_R + m_\mu \bar{\mu}_L \mu_R + m_\tau \bar{\tau}_L \tau_R) H^0 + h_{ij}^l \bar{l}_{iL} l_{jR} \phi^0 \\ & + \frac{\sqrt{2}}{v} (m_d \bar{d}_L d_R + m_s \bar{s}_L s_R + m_b \bar{b}_L b_R) H^0 + h_{ij}^d \bar{d}_{iL} d_{jR} \phi^0 \end{aligned} \quad (2)$$

where the neutral components consist of

$$\begin{aligned} H^0 &= \frac{1}{\sqrt{2}} (v + H_s + iG^0), \\ \phi^0 &= \frac{1}{\sqrt{2}} (\phi_s + i\phi_p), \end{aligned} \quad (3)$$

with the scalars  $H_s$  and  $\phi_s$ , Goldstone mode  $G^0$ , and the pseudoscalar  $\phi_p$ . Assuming that the CP is conserved in the Higgs sector, the physical states of CP-even scalars,  $h$  and  $H$  are defined through the mixing

$$\begin{pmatrix} \phi_s \\ H_s \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}, \quad (4)$$

and the CP-odd scalar  $A = \phi_p$ .

The SM-like Higgs boson  $h$  decays into the LFV final states through the small mixing  $\sin \theta$ . The decay width is given by

$$\Gamma(h \rightarrow \mu\tau) = \frac{m_h \sin^2 \theta}{16\pi} (|h_{\mu\tau}|^2 + |h_{\tau\mu}|^2), \quad (5)$$

and the corresponding branching fraction given by  $\text{Br}(h \rightarrow \mu\tau) = \Gamma(h \rightarrow \mu\tau)/(\Gamma_{SM} + \Gamma(h \rightarrow \mu\tau))$ . From now on the Yukawa couplings are assumed to be real and  $h_{\mu\tau} = h_{\tau\mu}$  for simplicity. Thus we obtain the combined parameter  $h_{\mu\tau} \sin \theta$ ,

$$h_{\mu\tau}^2 \sin^2 \theta = \frac{8\pi}{m_h} \Gamma_{SM} \frac{\text{Br}(h \rightarrow \mu\tau)}{1 - \text{Br}(h \rightarrow \mu\tau)} \approx 0.68 \times 10^{-5} \left( \frac{\text{Br}(h \rightarrow \mu\tau)}{0.82\%} \right). \quad (6)$$

The LFV scalar interactions also induce new contributions to the muon anomalous magnetic moment,  $(g-2)_\mu$ . Still the experimental data of  $(g-2)_\mu$  shows a deviation more than  $3\text{-}\sigma$  from the SM prediction as,

$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (288 \pm 63 \pm 49) \times 10^{-11}, \quad (7)$$

where the first error is experimental and the second theoretical. The LFV scalar interaction is one of the good candidates to cure this disagreement of  $(g-2)_\mu$  between theory and experiments. The leading contribution to the  $(g-2)_\mu$  are given by

$$\Delta a_\mu = \frac{h_{\mu\tau}^2}{16\pi^2} m_\mu m_\tau \left[ \frac{\sin^2 \theta}{m_h^2} \left( \log \frac{m_h^2}{m_\tau^2} - \frac{3}{2} \right) + \frac{\cos^2 \theta}{m_H^2} \left( \log \frac{m_H^2}{m_\tau^2} - \frac{3}{2} \right) - \frac{1}{m_A^2} \left( \log \frac{m_A^2}{m_\tau^2} - \frac{3}{2} \right) \right], \quad (8)$$

in the general 2HD model. We note that the SM Higgs contribution of the first term in Eq. (8)  $\sim 4.4 \times 10^{-12}$  with the value of Eq. (6), which could not explain the deviation and additional contribution of  $H$  are inevitable to accommodate  $\Delta a_\mu$  in this model.

Although the SM Higgs boson may not be the lightest scalar in the general 2HDM, we assume the conservative condition  $m_H, m_A \geq m_h$  in this analysis and do not consider the constraints from the direct detection of scalars at colliders.

### III. LFV $\tau$ DECAYS

The Higgs FCNC couplings lead to the various LFV decay processes, which do not exist in the SM. In this letter, we focus only on the scalar- $\mu$ - $\tau$  coupling and the relevant LFV decays are  $\tau \rightarrow \mu\gamma$  and  $\tau \rightarrow \mu\mu\mu$ . The strong experimental limits are given by  $\text{Br}(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$  and  $\text{Br}(\tau \rightarrow \mu\mu\mu) < 2.1 \times 10^{-8}$  [6].

We write the effective lagrangian for electromagnetic penguin operators as

$$\mathcal{L}_{\text{eff}} = C_L \mathcal{O}_L + C_R \mathcal{O}_R + \text{H.c.}, \quad (9)$$

where the operators are given by

$$\mathcal{O}_{L,R} = \frac{e}{8\pi^2} m_\tau (\bar{\mu} \sigma^{\mu\nu} P_{L,R} \tau) F_{\mu\nu} \quad (10)$$

and the leading contributions to the one-loop and two-loop Wilson coefficients by [13]

$$\begin{aligned} C_{L,R}^{(1)} &\approx \frac{1}{4m_h^2} \frac{m_\tau}{v} h_{\mu\tau} \cos \theta \left( \log \frac{m_h^2}{m_\tau^2} - \frac{4}{3} \right) \\ C_{L,R}^{(2)} &\approx 0.055 h_{\mu\tau} \frac{1}{(125 \text{ GeV})^2}. \end{aligned} \quad (11)$$

Note that the one-loop contributions involve the  $\tau$  internal line diagrams and the two-loop contributions come from the Barr-Zee type diagrams. The branching ratio for  $\tau \rightarrow \mu\gamma$  decay is

$$\text{Br}(\tau \rightarrow \mu\gamma) = \tau_\tau \frac{\alpha m_\tau^5}{64\pi^4} (|C_L|^2 + |C_R|^2), \quad (12)$$

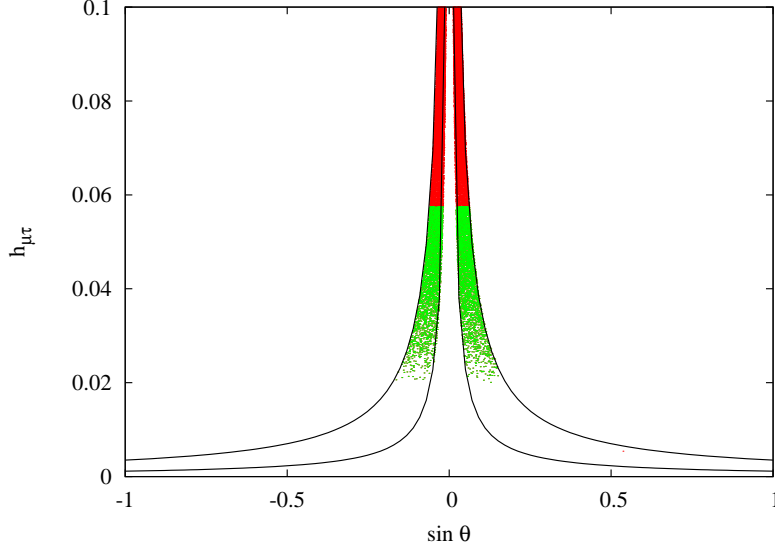


FIG. 1. Allowed parameter sets of  $(\sin \theta, h_{\mu\tau})$ . The region between curves denotes the parameters allowed by  $h \rightarrow \mu\tau$  decays, the red dots are constrained by  $(g - 2)_\mu$ , and the green dots additionally constrained by LFV  $\tau \rightarrow \mu\gamma$  and  $\tau \rightarrow \mu\mu\mu$ .

where  $\tau_\tau$  is the tau lifetime.

Due to the Higgs LFV coupling, the  $\tau \rightarrow \mu\mu\mu$  decay is obtained at tree level through the Higgs mediated diagram. The branching ratio for  $\tau \rightarrow \mu\mu\mu$  decay is given by

$$\text{Br}(\tau \rightarrow \mu\mu\mu) = \tau_\tau \frac{m_\tau^5}{3072\pi^3} h_{\mu\tau}^2 \left( \left| \frac{\sin \theta}{m_h^2} y_{h\mu\mu} - \frac{\cos \theta}{m_H^2} y_{H\mu\mu} \right|^2 + \left| \frac{1}{m_A^2} y_{A\mu\mu} \right|^2 \right), \quad (13)$$

where the lepton flavour conserving Higgs couplings are

$$\begin{aligned} y_{h\mu\mu} &= \frac{m_\mu}{v} \cos \theta - \frac{h_{\mu\mu}}{\sqrt{2}} \sin \theta, \\ y_{H\mu\mu} &= \frac{m_\mu}{v} \sin \theta + \frac{h_{\mu\mu}}{\sqrt{2}} \cos \theta, \\ y_{A\mu\mu} &= \frac{h_{\mu\mu}}{\sqrt{2}}, \end{aligned} \quad (14)$$

where the new flavour conserving coupling  $h_{\mu\mu}$  is assumed to be the same order of the ordinary Yukawa coupling  $\sim m_\mu/v$  here.

Figure 1 depicts the allowed values of the mixing angle  $\sin \theta$  and the LFV coupling  $h_{\mu\tau}$ . The region between the curves explains the  $h \rightarrow \mu\tau$  decays. The red dots (overlapped by green dots) are allowed values by  $\Delta a_\mu$  and the green dots allowed by additional constraints  $\text{Br}(\tau \rightarrow \mu\gamma)$ , and  $\text{Br}(\tau \rightarrow \mu\mu\mu)$  data. We can see that the upper bound on  $h_{\mu\tau} \sim 0.06$  is directly obtained by the limits of LFV  $\tau$  decays. Note that the mixing angle might be large if  $h_{\mu\tau}$  is small enough. Then the  $H$  can be light with small  $\cos \theta$ . Since the sizable  $H$  contribution is required to accommodate  $\Delta a_\mu$ , the  $H$  mass is upper bounded depending upon  $h_{\mu\tau}$  as shown in Fig. 2. We also show the allowed masses of  $H$  and  $A$  in Fig.3. We find that the  $H$  mass has the upper bound  $\sim 420$  GeV by the  $\tau$  decays, while no limits are attributed to the  $A$  mass. Moreover the negative contribution of  $A$  cancels the  $H$  contribution in  $\Delta a_\mu$  calculation and both of the  $H$  and  $A$  could be very light simultaneously.

#### IV. LFV $B_s \rightarrow \mu\tau$ DECAYS

Study of the  $B_s$  phenomenology has been performed at the Tevatron and becomes animated at the LHCb. The  $B_s$  meson provides good probes to the NP since it involves relatively large FCNC interactions.

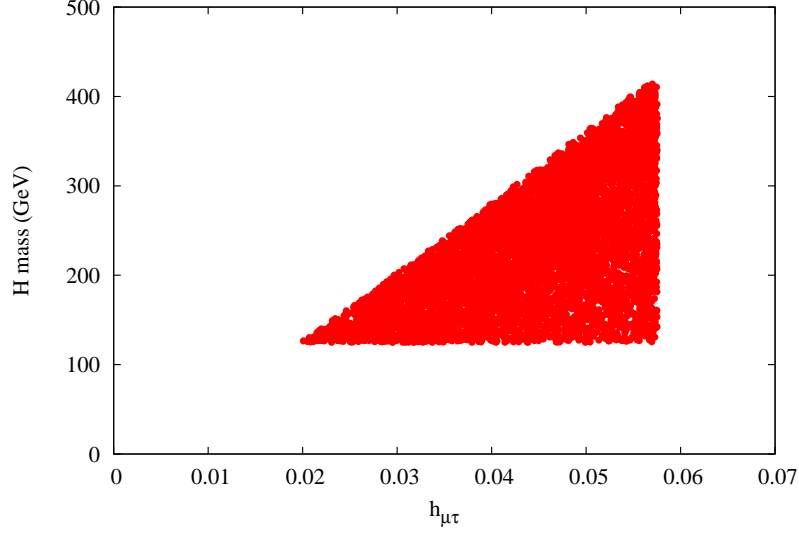


FIG. 2. Allowed masses of  $H$  with respect to  $h_{\mu\tau}$  by  $h \rightarrow \mu\tau$  decays,  $(g-2)_\mu$ ,  $\tau \rightarrow \mu\gamma$ , and  $\tau \rightarrow \mu\mu\mu$  decays.

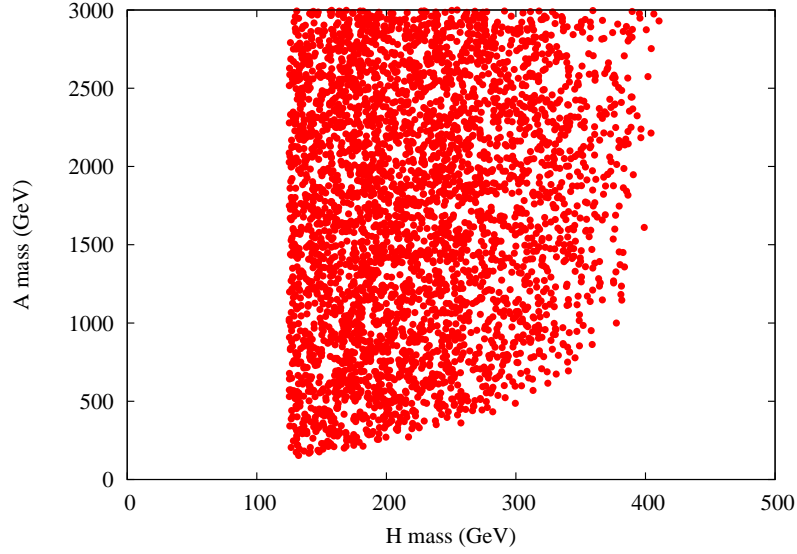


FIG. 3. Allowed masses of  $H$  and  $A$  by  $h \rightarrow \mu\tau$  decays,  $(g-2)_\mu$ ,  $\tau \rightarrow \mu\gamma$ , and  $\tau \rightarrow \mu\mu\mu$  decays.

The relevant terms of the effective Hamiltonian for  $B_s$  decays contributing to the LFV decays of  $B_s$  mesons are

$$\mathcal{H}_{\text{eff}} = -\frac{G_F^2 M_W^2}{\pi^2} V_{tb}^* V_{ts} (C_{10} \mathcal{O}_{10} + C_S \mathcal{O}_S + C_P \mathcal{O}_P) + H.c. , \quad (15)$$

where the operators are given by

$$\begin{aligned} \mathcal{O}_{10} &= (\bar{b}_R \gamma^\mu s_L)(\bar{\mu} \gamma_\mu \gamma_5 \tau), \\ \mathcal{O}_S &= m_b (\bar{b}_R s_L)(\bar{\mu} \tau), \\ \mathcal{O}_P &= m_b (\bar{b}_R s_L)(\bar{\mu} \gamma_5 \tau). \end{aligned} \quad (16)$$

The Wilson coefficients are obtained from the  $h$ ,  $H$ , and  $A$  exchange diagrams in this model,

$$C_S = -\frac{\pi^2}{2G_F^2 M_W^2 (V_{tb}^* V_{ts})} \frac{h_{bs} h_{\mu\tau}}{m_b} \left( \frac{\sin^2 \theta}{m_h^2} + \frac{\cos^2 \theta}{m_H^2} \right),$$

$$C_P = \frac{\pi^2}{2G_F^2 M_W^2 (V_{tb}^* V_{ts})} \frac{h_{bs} h_{\mu\tau}}{m_b} \frac{1}{m_A^2}. \quad (17)$$

We also assume that  $h_{bs} = h_{sb}$  and is real for simplicity. Then the branching ratio of  $B_s$  mesons are given by

$$\begin{aligned} \text{Br}(B_s \rightarrow \mu\tau) &= \frac{G_F^4 M_W^4}{8\pi^5} |V_{tb}^* V_{ts}|^2 M_{B_s}^5 f_{B_s}^2 \tau_{B_s} \left( \frac{m_b}{m_b + m_s} \right)^2 \\ &\times \sqrt{\left( 1 - \frac{(m_\tau + m_\mu)^2}{M_{B_s}^2} \right) \left( 1 - \frac{(m_\tau - m_\mu)^2}{M_{B_s}^2} \right)} \\ &\times \left[ \left( 1 - \frac{(m_\tau + m_\mu)^2}{M_{B_s}^2} \right) |C_S|^2 + \left( 1 - \frac{(m_\tau - m_\mu)^2}{M_{B_s}^2} \right) |C_P|^2 \right]. \end{aligned} \quad (18)$$

The quark sector FCNC coupling  $h_{bs}$  is constrained by the  $B$  physics data. We consider the  $B_s - \bar{B}_s$  mixing as a constraint for  $h_{bs}$ . The present measurement of the mass difference  $\Delta M_s$  [6]

$$\Delta M_s = 17.756 \pm 0.021 \quad (19)$$

in  $10^{12} \hbar \text{ s}^{-1}$ . The  $\Delta M_s$  in the general 2HDM reads [12]

$$\Delta M_s = \Delta M_s^{\text{SM}} + 2h_{bs}^2 \left[ \frac{\sin^2 \theta}{m_h^2} \Delta_h + \frac{\cos^2 \theta}{m_H^2} \Delta_H - \frac{1}{m_A^2} \Delta_A \right], \quad (20)$$

where

$$\Delta_S = \sum_{i=1,2} (C_{Si}^{SLL}(\mu) \langle O_i^{SLL}(\mu) \rangle + C_{Si}^{SRR}(\mu) \langle O_i^{SRR}(\mu) \rangle + C_{Si}^{LR}(\mu) \langle O_i^{LR}(\mu) \rangle), \quad (21)$$

and  $S = h, H, A$  with the Wilson coefficients

$$\begin{aligned} C_{S1}^{SLL}(\mu) &= C_{S1}^{SRR}(\mu) = 1 + \frac{\alpha_s}{4\pi} \left( -3 \log \frac{m_S^2}{\mu^2} + \frac{9}{2} \right) \\ C_{S2}^{SLL}(\mu) &= C_{S2}^{SRR}(\mu) = \frac{\alpha_s}{4\pi} \left( -\frac{1}{12} \log \frac{m_X^2}{\mu^2} + \frac{1}{8} \right) \\ C_{S1}^{LR}(\mu) &= -\frac{3}{2} \frac{\alpha_s}{4\pi}, \quad C_{S2}^{LR}(\mu) = 1 - \frac{\alpha_s}{4\pi}, \end{aligned} \quad (22)$$

and the matrix elements estimated to be

$$\begin{aligned} \langle O_1^{SLL}(1 \text{ TeV}) \rangle &= -0.17, & \langle O_2^{SLL}(1 \text{ TeV}) \rangle &= -0.33, \\ \langle O_1^{LR}(1 \text{ TeV}) \rangle &= -0.37, & \langle O_2^{LR}(1 \text{ TeV}) \rangle &= 0.51, \\ \langle O_1^{SLL}(m_t) \rangle &= -0.14, & \langle O_2^{SLL}(m_t) \rangle &= -0.29, \\ \langle O_1^{LR}(m_t) \rangle &= -0.30, & \langle O_2^{LR}(m_t) \rangle &= 0.40, \end{aligned} \quad (23)$$

in  $(\text{GeV})^3$ . We note that  $C_i^{SLL} = C_i^{SRR}$ ,  $\langle O_1^{SLL} \rangle = \langle O_1^{SRR} \rangle$ . The mass scale is taken to be  $\mu = m_t(m_t)$  if  $m_{H,A} < 1 \text{ TeV}$  and  $\mu = 1 \text{ TeV}$  elsewhere.

Figure 4 show the branching ratio  $\text{Br}(B_s \rightarrow \mu\tau)$  with respect to  $m_H$ . We find that the decay rates are substantial and even there exists some minimum value of the branching ratio,  $\sim 3.5 \times 10^{-8}$ . Such large  $B_s \rightarrow \mu\tau$  decay rates are caused by the  $H$  exchange contribution. Contributions of the CP-odd scalar  $A$  might play a role for the decays since it cancels the  $H$  contribution in  $\Delta a_\mu$  but constructive in the  $B_s$  decay rates.

Observation of the LFV  $B_s \rightarrow \mu\tau$  decays is a very clear evidence of the NP independent of the  $h \rightarrow \mu\tau$  decays. Although the detection of  $\tau$  is challenging at the LHCb, we expect that it will be possible to observe  $B_s \rightarrow \mu\tau$  decays in the future by achieving an improvement of the  $\tau$  identification in the experiment.

## V. CONCLUDING REMARKS

Inspired by the recent measurements of LFV  $h \rightarrow \mu\tau$  decays, we suggest an exotic  $B_s$  decays into  $\mu\tau$  final states as a new signature of the LFV scalar interactions in the general 2HDM. In order to accommodate the  $\Delta a_\mu$  with the scalar FCNC in this model, sizable contributions of additional scalars other than the SM Higgs boson are required. We find

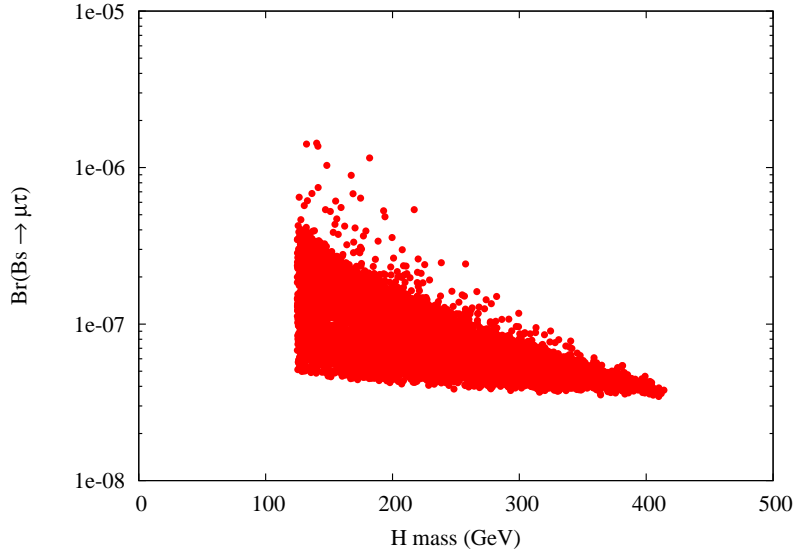


FIG. 4. Branching ratios of  $B_s \rightarrow \mu\tau$  decays with respect to  $m_H$  which explain  $h \rightarrow \mu\tau$  decays and allowed by  $(g-2)_\mu$ ,  $\tau \rightarrow \mu\gamma$ , and  $\tau \rightarrow \mu\mu\mu$  decays.

that the scalar FCNC contributions to  $\Delta a_\mu$  also induce large contribution to  $B_s \rightarrow \mu\tau$  decays and the considerable decay rates of the decay are possible. We show that the branching ratio is larger than  $\mathcal{O}(10^{-8})$  and even could be of order  $\sim 10^{-5}$ . Such a large decay rate is expected to be measured at the LHCb if  $\tau$  detection is improved.

The scalar FCNC couplings in the quark sector,  $h_{bs}$  are also essential to  $B_s \rightarrow \mu\tau$  decays and constrained by the  $B_s - \bar{B}_s$  mixing data. The  $bs$  FCNC couplings also lead to the NP contribution to  $B_s \rightarrow \mu^- \mu^+$  decays in general, of which recent measurement agrees with the SM prediction. However our assumption of real  $h_{bs} = h_{sb}$  makes NP contributions proportional to  $h_{bs}$  and  $h_{sb}$  cancel each other and thus we consider no limits from  $B_s \rightarrow \mu^- \mu^+$  decays in this work.

## ACKNOWLEDGEMENTS

KYL is supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT and Future Planning (Grant No. NRF-2015R1A2A2A01004532).

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